Developing and Evaluating an Eighth Grade Curriculum Unit That Links Foundational Chemistry to Biological Growth

Paper #1: Selecting Core Ideas and Practices – An Iterative Process

Jo Ellen Roseman, Cari Herrmann Abell, and Jean Flanagan
AAAS Project 2061

Rebecca Kruse, Elaine Howes, Janet Carlson, Kathy Roth, and Brooke Bourdélat-Parks
BSCS

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ABSTRACT

Researchers at AAAS and BSCS have developed a six-week unit that aims to help middle school students learn important chemistry ideas that can be used to explain growth and repair in animals and plants. By integrating core physical and life science ideas and engaging students in the science practices of modeling and constructing explanations, the unit is designed to address major recommendations in national standards documents, including the National Research Council's *A Framework for K-12 Science Education* (2012). In this paper, the authors focus on the iterative design process used to select and refine a set of learning goals for the unit that target the three dimensions of science learning identified in the *Framework*—science core ideas, science practices, and crosscutting concepts. The paper also describes the data on alignment, classroom implementation, and student and teacher learning that informed the revision of the learning goals through three iterations of the unit. Numerous examples are provided to illustrate the kinds of design issues that arose and how they were resolved to address the challenges inherent in taking a standards-based approach to curriculum design.

Introduction

In 2009 the American Association for the Advancement of Science (AAAS) and the Biological Sciences Curriculum Study (BSCS) were funded by the U.S. Department of Education's Institute for Education Sciences to develop a new curriculum unit that would prepare middle school students for success in high school biology. In the proposal for that work, we provided a rationale for why such a unit was needed, and, in particular, focused on the need to address an important, but often overlooked, set of ideas that integrate knowledge from the physical and life sciences in order to provide the chemistry foundation for biology. As was noted in the proposal, the need for curriculum materials that address these ideas was driven largely by the nature of modern biology itself, which, according to the National Research Council depends more than ever on chemistry:

> Much of modern biology has become increasingly chemical in character. This has always been true of biochemistry and medicinal chemistry, but molecular biology, genetics, cell biology, proteomics, physiology, microbiology, neurobiology, agriculture, and many other divisions of biology are now using chemistry as a major part of their language and their research. The trend will continue, as more and more biological phenomena are explained in fundamental chemical terms. (National Research Council [NRC], 2003, p. 136)

What is more, the proposal acknowledged that even those students who appear to grasp the fundamentals of middle school chemistry often exhibit difficulty applying molecular principles to living organisms (Mohan, Chen, & Anderson, 2009; DeBoer, Herrmann Abell, Wertheim, & Roseman, 2009). Our proposal argued that "without a strong understanding of core chemistry and biochemistry science standards in middle school, most students are not likely to make progress toward more advanced study of biology or other science courses in high school or beyond."

In addition to addressing an integrated set of physical and life science content learning goals, we also intended to use the unit as an opportunity to help students understand and engage in the key scientific practices of modeling and constructing explanations. With the publication in 2012 of *A Framework for K-12 Science Education* by the National Research Council (NRC), we found new support in that document's call for "curricular and instructional materials that embody all three dimensions: scientific and engineering practices, crosscutting concepts, and disciplinary core ideas" (p. 316). The *Toward High School Biology* (THSB) unit is being developed by AAAS and BSCS to meet these specifications, and we believe that both the unit and its development process can serve as a model for other curriculum development efforts. In this paper, we focus on one aspect of that process: the selection of the learning goals for the unit and the multiple sources of data used to revise and improve the unit's coherence and efficiency in addressing those goals.

Designing a unit to meet such a complex set of specifications presented numerous challenges, not the least of which was taking on the traditional scope and sequence of the middle school science curriculum, which rarely juxtaposes the teaching of related concepts such as chemical reactions in physical and life science. Most publishers of traditional middle school science textbooks produce materials for year-long discipline-based courses. Life science textbooks include net reactions of photosynthesis and cellular respiration without basic principles of atom rearrangement and conservation, and physical science textbooks include no life science examples when introducing chemical changes. In most school districts,

life science is offered in the seventh grade and physical science is offered in the eighth grade, so students encounter photosynthesis and cellular respiration before they are taught what chemical reactions are. Modular programs typically have separate units for life and physical science that can be used in any sequence (Kesidou & Roseman, 2002; Stern & Roseman, 2004), but connections between the unit may not be made clear to students. Even a more recent multi-year program such as the *Investigating and Questioning Our World Through Science and Technology* (IQWST) curriculum developed by researchers at the University of Michigan and Northwestern University, presents chemical reactions in physical and life science in separate grades (Krajcik & Reiser, 2007). Thus the THSB unit is unique in treating these ideas together and taught by the same teacher so that connections among the ideas are more likely to be made.

The development of the THSB unit was guided by criteria for content coherence (Roseman, Stern, & Koppal, 2010) and by criteria for judging the quality of instructional support that had been used in Project 2061's middle school science textbook analyses (Kesidou & Roseman, 2002; Stern & Roseman, 2004). Content coherence required (a) the presentation of a set of important age-appropriate science ideas and connections among them, (b) the use of representations to clarify the ideas and connections, (c) inclusion of a range of relevant phenomena to illustrate the science ideas and their explanatory power, and (d) the avoidance of unnecessary technical terms or details that are likely to distract students from the main story (p. 50). As was noted in Roseman, Stern, and Koppal, 2010:

> Our approach to analyzing content coherence can also play a role in the development of new curriculum materials by providing developers with methods for taking a more systematic look at the overall structure and narrative of their materials and how the individual pieces fit together. The approach can help developers to describe the conceptual story to be presented in a material, identify the specific learning goals to be targeted, and clarify the connections to be made among the relevant ideas. Taking this approach generates a set of content design specifications to guide the material's development at each stage of the process." (p. 63)

Satisfying the instructional quality criteria required that the unit identify and maintain a sense of purpose, take account of student ideas, engage students in observing and modeling phenomena, guide students in interpreting their experiences with phenomena and models in terms of the science ideas, and support students in reflecting on applying science ideas (Kesidou & Roseman, 2002). Together, the set of content coherence and instructional support criteria had implications for the selection and clarification of learning goals. To have a coherent content storyline, the unit would have to start with learning goals that would hang together conceptually. To satisfy the instructional criteria, which required that considerable time be devoted to developing student understanding, the number of learning goals would have to be kept small.

We are currently in the final year of the project. In the first year, we pilot tested an initial version of the unit with a small number of schools (Herrmann-Abell et al., 2012). Data from the Year 1 pilot test was used to revise both the learning goals that the unit would target in Year 2 and the Year 2 version of the unit itself. This paper, which is one of a set of five related papers, focuses on (a) revisions to the learning goals for Year 2, including how they were selected and clarified, and (b) how data from the Year 2 implementation of the unit—i.e., data from an analysis of curriculum quality, data on classroom feasibility, and data on student learning—informed another round of revisions of the learning goals for the Year 3 version of the unit. The paper concludes with a discussion of implications for the design of materials in general and, in particular, for the successful implementation of the integrated learning of science ideas, practices, and cross-cutting concepts as envisioned in *A Framework for K-12 Science Education* (National Research Council [NRC], 2012).

Other papers in this set detail the iterative development and revision of the student materials and of teacher support materials and professional development, the development of measures of students' understanding and findings from the Year 2 pilot test of the unit, and the development and testing of measures of teachers' knowledge of the content and curriculum, all based on the Year 2 version of the unit. The *Toward High School Biology* project is funded by a Development and Innovation grant from the U.S. Department of Education's Institute for Education Sciences to develop and study the feasibility and usability of the curriculum unit and a suite of teacher support materials.

Selection and Clarification of Learning Goals for the Year 2 Unit

The selection of the learning goals to serve as targets for both curriculum and assessment design was guided by the criteria first outlined in *Science for All Americans* (*SFAA*) (American Association for the Advancement of Science [AAAS], 1989): utility, social responsibility, the intrinsic value of knowledge, philosophical value, and childhood enrichment (p. 21). *Benchmarks for Science Literacy* (*Benchmarks*) (AAAS, 1993) had "back mapped" the adult science literacy goals in *SFAA* to produce specific, age-appropriate statements of what K-12 students should know and be able to do that drew upon and referenced available learning research. The NRC had produced a similar set in *National Science Education Standards* (NSES) (NRC, 1996) that drew extensively on *SFAA* and *Benchmarks*.
The overarching goal of the *Toward High School Biology* unit is for students to use ideas about what happens to atoms and molecules during chemical reactions to explain growth and repair in living things. The identification of more specific learning goals was influenced by national content standards (which embodied criteria of importance, specificity, and age appropriateness and encompassed cross-cutting concepts and scientific practices as well as core science ideas), by a commitment to helping students build a coherent and useful understanding of relevant phenomena, and by what could realistically be achieved in a six-week unit.

Core Science Ideas

For the initial design of the Year 1 version of the unit, the research team began by targeting a small number of ideas about chemical reactions in physical and life science that were included in *Benchmarks*. The *NSES* had postponed ideas about the molecular basis of chemical reactions until high school and, therefore, provided little guidance. Because of the close resemblance between *Benchmarks* and the NRC *Framework* on these topics, this paper will use the language of the more recent *NRC Framework* to characterize the learning goals targeted in the unit.

In physical science, the eighth grade core ideas about chemical reactions focus on atom rearrangement as an explanation for producing substances with different properties and on atom conservation as an explanation for mass conservation. The ideas in boldface below were targeted in the unit:

> *By the end of grade 8.* **Substances react chemically in characteristic ways. In a chemical process, the atoms that make up the original substances are regrouped into different molecules, and these new substances have different properties from those of the reactants. The total number of each type of atom is conserved, and thus the mass does not change.** Some chemical reactions release energy, others store energy. (NRC, 2012, p. 111)

In life science, the eighth grade core ideas about chemical reactions link matter transformation and energy flow in photosynthesis and cellular respiration to the growth and functioning of organisms:

> *By the end of grade 8.* **Plants**, algae (including phytoplankton), and many microorganisms use the energy from light to **make sugars (food) from carbon dioxide from the atmosphere and water through the process of photosynthesis, which releases oxygen. These sugars can be used** immediately or stored **for growth** or later use. **Animals obtain food from eating plants or**

> **eating other animals. Within individual organisms, food moves through a series of chemical reactions in which it is broken down and rearranged to form new molecules, to support growth,** or to release energy. In most animals and plants, oxygen reacts with carbon-containing molecules (sugars) to provide energy and produce carbon dioxide; anaerobic bacteria achieve their energy needs in other chemical processes that do not require oxygen. (NRC, 2012, p. 148)

The parts of the core ideas not in boldface describe the role of energy in chemical reactions. We decided not to target these energy ideas for both practical and conceptual reasons. Prior work by AAAS and others had indicated that most students lacked mental models for thinking about either matter transformation or energy transformation and found these ideas to be particularly difficult (Herrmann-Abell & Roseman, 2008; Liu & Lesniak,2006; Anderson, Sheldon, & DuBay, 1990). We did not believe that the six weeks of instructional time that our school district partners were willing to devote to the topic of chemical reactions would be sufficient to develop a coherent treatment of both matter transformation and energy transformation. Therefore, we decided not to tackle both. Because matter transformation and conservation could be made concrete with physical models, we opted to emphasize those core ideas. Nevertheless, in the Year 1 version of the unit, we decided to include a single idea about energy (Atoms don't turn into energy and energy doesn't turn into atoms.) in order to address a common misconception. Although we found a decrease in the prevalence of the matter-from-energy misconception when students used the Year 1 version of the unit, we also observed that (a) only a few students invoked the idea when challenging their classmates' explanations and (b) only a few students were able to use an atomic/molecular model to explain chemical reactions in open systems. With such a small payoff and much more work to be done on the energy transformation ideas, we focused the Year 2 version of the unit on matter ideas only and omitted all mention of energy ideas.

The *core ideas* about matter were unpacked to *learning goals* and then further unpacked to finer grain *science ideas* that could serve as the basis for curriculum design (Heller, 2001; Krajcik, McNeill, & Reiser, 2008). Roseman, Stern, and Koppal (2010) defined science ideas as "propositions that can be investigated and hence supported or refuted by data [and] are at the grain size of what can be rejected or believed based on evidence and thereby remembered and connected to other ideas" (p. 49). A similar unpacking led to the specification of a related set of ideas to serve as the basis for assessment design (Herrmann-Abell, et al., 2013).

The complete set of learning goals and science ideas targeted in the Year 2 version of the unit can be found in Tables 1a and 1b. Included in the physical science list were science ideas about the formation of new substances during chemical reactions, atom rearrangement during chemical reactions, and mass conservation in chemical reactions. For example, science ideas about atom rearrangement included an idea that links atom rearrangement to the formation of new substances (The properties of a substance are determined by the different type, number, and arrangement of atoms that make up the molecules of the substance.) and two ideas that would be useful for linking atom rearrangement to growth:

- Small molecules made up of carbon chains (monomers) can link together during chemical reactions to form large molecules (polymers) and water molecules. Monomers usually have groups of atoms—either oxygen and hydrogen atoms or nitrogen and hydrogen atoms—at two places on the molecule that are important for linking the monomers.
- Atoms still rearrange when polymers form, even though only a few are actually rearranged. Even though only a few atoms rearrange, polymer formation is a type of chemical reaction. The polymer is a new substance and has different properties than the monomers from which it formed.

Because biological growth results primarily from polymerization reactions, we decided to introduce polymer formation as an instance of chemical reactions in the physical science lessons (which precede the biochemistry lessons) and to introduce the terms *monomer* and *polymer* to facilitate communication about this type of chemical reaction.

For conservation of matter, we included a science idea that would reconcile conservation principles with changes in mass that students would observe through classroom demonstrations or through their own firsthand experiences carrying out chemical reactions and using a variety of physical models to represent them. During the pilot of the Year 1 version of the unit, students had considerable difficulty reconciling the law of conservation of matter with observed mass changes in open systems. We decided to explicitly confront this seeming inconsistency through modeling activities and by elaborating the conservation of matter learning goal to include the term *measured mass*: “If the measured mass changes during a chemical reaction, it is because one or more substances, usually gases, have entered or left.”

In the life science list for the Year 2 unit were science ideas about chemical reactions involved in growth of animals and plants, including the production of new substances, atom rearrangement, and conservation. Science ideas about the molecular composition of animals (mostly protein polymers, whose properties result from their amino acid composition and sequence) and plants (mostly carbohydrate polymers, whose properties result from the way glucose monomers are linked) related growth to the production of new substances through chemical reactions:

- Growth, repair, and replacement of animal body structures all involve chemical reactions during which proteins from food are used to make other proteins that become part of their body structures.
- Growth, repair, and replacement of plant body structures involve chemical reactions during which glucose molecules are used to make carbohydrate polymers. These carbohydrate polymers become part of the plant's body structures.

We decided to use protein and carbohydrate synthesis as examples of polymerization reactions in living systems because (a) in both cases the polymer was a simple chain of individual monomers and (b) protein polymers and carbohydrate polymers are the primary structural polymers of animal and plant bodies, respectively. Fats were excluded because they did not meet these criteria and because the chemical reactions involved in lipid synthesis are more complex. Other science ideas about how plants make amino acids from glucose and nitrogen and then use the amino acids to make proteins were included to explain how herbivores and vegans obtain proteins and why most of the mass of a tree doesn’t come from the soil.

We decided to “black box” events related to biological growth and repair at the cellular level. Properties of the biomaterials (protein polymers, carbohydrate polymers, and composites of them) provide a more powerful—and demonstrable—explanation for the properties of body structures (e.g., muscle tissue or plant stems) than the fact that they are made up of cells, and the role of cells in biosynthesis would have distracted from the central storyline. Moreover, we thought that a consistent focus on linking mass/matter/materials/atoms to growth would be more likely to extinguish the common student misconception that cell division alone accounts for growth, which tends to be reinforced by existing curriculum materials.

Science Practices

To help students understand the link between phenomena involving the growth of animals and plants and underlying molecular events, the Year 2 curriculum unit included activities that gave students opportunities to engage in modeling and explanation practices. Although the *NRC Framework* specifies

science practices only at grade 12, we decided that the following aspects of those practices would be appropriate for and helpful to eighth grade students:

Developing and using models:

- Construct drawings or diagrams as representations of events or systems.
- Represent and explain phenomena with multiple types of models—for example, represent molecules with 3-D models or with bond diagrams—and move flexibly between model types when different ones are most useful for different purposes. (NRC, p. 58)

Constructing explanations:

- Construct their own explanations of phenomena using their knowledge of accepted scientific theory and linking it to models and evidence.
- Use primary or secondary scientific evidence and models to support or refute an explanatory account of a phenomenon. (NRC, p. 69)

In addition, we thought it might be possible for students to also learn something about the nature of science as they engaged in using models to think about "processes that happen on too small a scale to observe directly" (AAAS, 2007, p. 93) and in writing explanations that link evidence to claims. Such experiences could serve as occasions to reflect on the importance to the scientific endeavor of evidence, models, and logical reasoning linking evidence to claims. Ideas about how science works are explicit learning goals in *Benchmarks* (p. 12 and 269). While the *NRC Framework* had not identified ideas about the nature of science as core goals for student learning, the conclusion to the chapter on scientific practices confirms that such ideas are indeed worth knowing: "Our view is that the opportunity for students to learn the basic set of practices outlined in this chapter is also an opportunity to have them stand back and reflect on how these practices contribute to the accumulation of scientific knowledge"(p. 78).

Crosscutting Concepts

To help students appreciate the links between physical and life science, the Year 2 version of the unit addressed the second dimension of the *NRC Framework* by focusing on the crosscutting concept of Energy and Matter: Flows, Cycles, and Conservation:

> The core ideas of matter and energy and their development across the grade bands are spelled out in detail in Chapter 5. What is added in this crosscutting discussion is recognition that an understanding of these core ideas can be informative in examining systems in life science, earth and space science, and engineering contexts. (NRC, p. 95)

In the late 1980s, AAAS's *Science for All Americans* had already identified a set of crosscutting themes, including ideas about systems and conservation, which were considered to be essential to science literacy and "tools for thinking about how the world works" (p. 19). The THSB unit was designed to address these themes as well.

Data That Informed Changes in the Learning Goals for the Year 3 Unit

Once the Year 2 version of the unit was ready for pilot testing in schools, the research team began to collect data from multiple perspectives that could be used to inform yet another round of revisions leading to the Year 3 version of the unit. As part of this process, the learning goals were also examined and revised again based on data from a page-by-page analysis of the Year 2 version of the unit, data on how the Year 2 unit was actually implemented in the classroom, and data on learning by students who used the unit.

Analysis of the Year 2 Version of the Unit

The research team analyzed the Year 2 unit to determine (a) whether or not its activities aligned with the science ideas, science practices, and crosscutting concepts that had been selected as targets, (b) whether the unit used the science ideas to tell a coherent story, and (c) how much instructional time had been allocated for each learning goal. An analysis of instructional quality was also carried out, but while those findings informed curriculum revisions, they only indirectly informed revisions to the learning goals. For example, if the instructional analysis indicated that scaffolding for a particular activity was insufficient, then the research team could then consider adding more instructional time focused on that learning goal and possibly reducing the total number of science ideas to accommodate the change.

Alignment. The analysis of the unit's alignment to the selected learning goals was carried out at the grain size of individual science ideas and followed the guidelines for making judgments about alignment that had been established in AAAS Project 2061's earlier textbook evaluation studies (Kesidou & Roseman, 2002; Stern & Roseman, 2004; Roseman, Stern, & Koppal, 2010).

<u>Alignment to core science ideas.</u> The Year 2 version of the unit was found to align with all of the science ideas shown in Tables 1a and 1b. For example, for science ideas about the production of new substances, students observed the production of new substances or data documenting that new substances are produced; for science ideas involving atom rearrangement, students modeled the chemical reactions with LEGO® bricks or ball-and-stick models. To ensure that students made the link between classroom activities and science ideas, students were asked to list examples of each science idea at the end of relevant lessons. The teacher edition (TE) provided an answer key for each science idea activity. For instance, in Lesson 6 the TE included the following to illustrate what students might offer as a good example for the science idea about atom rearrangement during polymer formation:

> Atoms still rearrange when polymers form, even though only a few are actually rearranged. Even though only a few atoms rearrange, polymer formation is a type of chemical reaction. The polymer is a new substance and has different properties than the monomers from which it formed.
>
> *Example:*
> *In Lesson 7, we saw that only 5 atoms are involved in rearranging or making new connections between two monomers. Water forms when the oxygen atom and hydrogen atom from adipic acid link with a hydrogen atom (from the nitrogen) of hexamethylenediamine. The carbon from adipic acid links to the nitrogen atom of hexamethylenediamine. This can happen at two places on each monomer.*

<u>Alignment to modeling practices.</u> The Year 2 version of the unit was also found to align with modeling practices recommended in the *NRC Framework*. Unit activities engaged students in modeling practices to help them visualize atom rearrangement and matter conservation in a variety of chemical reactions, including those necessary for growth in animals and plants. For each chemical reaction for which they observed that new substances are produced, students (a) examined models of reactants and products to see that molecules of reactants and products are made of the same kinds of atoms and (b) took apart models of reactant molecules to show that those atoms are necessary and sufficient for building the product molecules. In addition to physical models and drawings, students also represented chemical reactions with word equations and chemical formulas.

The Year 2 unit also used models to help students reconcile the seeming discrepancy between conservation principles and mass changes. Students modeled what happens to the measured mass in closed systems (where the weight of LEGO® models of reactants in a sealed plastic bag is the same as

the weight of the LEGO® models of products) and in open systems (where the weight of LEGO® models of products could be either less than or more than the weight of LEGO® models of reactants). In the case of the reaction between $NaHCO_3$ and $HC_2H_3O_2$, students removed LEGO® models of CO_2 formed during the reaction from the balance to visualize why the mass decreased when the reaction container was opened. In the case of the reaction between Fe and O_2, students added LEGO® models of O_2 gas to the balance and reacted them with unreacted Fe atoms to visualize why the mass increased when the reaction container was opened. (The modeling activity was designed so that O_2 is limiting when the reaction is "carried out" in a closed baggie; the Fe atoms that remain can then react with O_2 from the air when the baggie is opened.)

Lastly, students used models to help them visualize data from radioactive labeling experiments. Such experiments were included to provide evidence that various chemical reactions—digestion of proteins from food and building of body proteins for growth, glucose synthesis from CO_2, and cellulose synthesis from glucose, for example—are required for the growth of living organisms.

Alignment to explanation practices. The Year 2 version of the unit was found to align with explanation practices recommended in the *NRC Framework*. Activities in six lessons required students to critique and write complete explanations of phenomena, i.e., explanations that included claim, evidence, and reasoning (McNeill & Krajcik, 2012) and supported students in developing their explanations by providing a variety of instructional scaffolds consistent with the cognitive apprenticeship model of instruction (Collins, Brown, & Newman, 1989). For example, in Lesson 7, students were asked to (a) critique two complete explanations in the text; (b) observe that a substance with different properties is produced when silver tarnishes; (c) observe models that show that during the chemical reaction that produces tarnished silver, atoms of Ag, S, and H rearrange; (d) examine a complete explanation of the reaction provided in the text; (e) critique the explanation and in so doing develop criteria for evaluating the quality of the explanations; and (f) use the criteria to develop and evaluate their own explanations for what happens when baking soda reacts with vinegar and when iron rusts (SE, p. 50-54). Over the six lessons for which complete explanations were required, students were given a chart with space for them to write in their own claim, evidence, and reasoning; reminders of what each element should include were gradually removed as students moved through the lessons and became more adept at developing their explanations. In addition, students were asked to provide evidence for their answers throughout the unit; the TE provided answers for the teacher.

Alignment to ideas about the nature of science. The Year 2 version of the unit was not designed to make ideas about the nature of science explicit. However, the analysis did identify opportunities in the unit for providing examples of how science works. For instance, students consistently used models to "think about processes that…happen on too small a scale to observe directly" (AAAS, 2007, p. 93) and occasionally were asked to "reflect on how using models helps you understand science." Moreover, students' experiences writing and critiquing explanations provided opportunities for reflection about the role of evidence in science, but to take advantage of those opportunities would have required that instructional time be devoted to reflection. To maintain the coherence of the content storyline, the research team reluctantly decided not to focus more instructional time on the nature of science learning goals. The Discussion section of this paper describes the implications of such design tradeoffs in more detail.

Alignment to crosscutting concepts. As has been noted, the THSB unit contrasts with currently available materials by treating chemical reactions in both the inanimate world and in living organisms together. As a result, students who complete the unit will encounter chemical reactions in both nonliving and living contexts, an approach that the AAAS-BSCS research team believes is inherently consistent with the recommendations of the NRC *Framework*. However, judging the alignment of the Year 2 unit to this

particular dimension of the *Framework* is somewhat problematic; although the NRC *Framework* makes reasonably clear that crosscutting concepts are not to be taught as individual learning goals, it provides no guidance on how such cross-discipline connections could actually be made. Nevertheless, the Year 2 version of the unit included several features that the research team believed would help students make connections across disciplines. In addition to providing both physical and life science examples in the same unit, the unit's lesson structure, use of models, and use of language also reinforced cross-discipline connections.

The lesson structure of the Year 2 unit reinforced similarities between chemical reactions in physical science and life science by starting with the production of new substances to establish that a chemical reaction had occurred in both contexts and then using LEGO® bricks and ball-and-stick models to represent atom rearrangement that occurs during those chemical reactions. Chemical reactions were first introduced in laboratory contexts, where properties of starting substances and some ending substances could be observed directly before moving to animal and plant growth, where data from radioactive labeling experiments were provided to demonstrate the production of new substances. Similarly, modeling atom rearrangement started with chemical reactions involving small molecules before moving to chemical reactions involving large molecules, such as nylon polymerization, protein digestion, and cellulose formation. Starting with simpler systems was intended to make substance formation and atom rearrangement become "tools for thinking" in more complex biological contexts, and this was reinforced by various tasks. For example, lessons on animal and plant growth explicitly asked students to compare nylon polymerization reactions encountered previously to protein and cellulose formation and to compare the source of the mass increase when iron rusts to the source of mass increase when plants grow.

Moreover, the models themselves reinforced the connections across disciplinary ideas. Textbooks typically show individual atoms when representing chemical reactions involving simple molecules (e.g., H_2O, CO_2, $NaHCO_3$, $HC_2H_3O_2$) but use a variety of shorthand conventions when representing complex biological molecules (e.g., representing glucose, cellulose, and starch using hexagons that do not show all the atoms and representing proteins with wire diagrams that do not show any atoms). Such shorthand representations are useful for communications among biochemists but not among novices. The Year 2 unit avoided using the scientific shorthand representations so that students could see which atoms were rearranged. This meant having students build only a few monomers and "react" them to form polymers and doing the same in drawings shown in the student materials.

Finally, the Year 2 unit used similar language for science ideas in physical and life science. For example, to emphasize the similarity between chemical reactions in open containers and animal growth, science ideas in both physical science and life science use the term *measured mass*:

> If the *measured mass* changes during a chemical reaction, it is because one or more substances, usually gases, have entered or left.
>
> When animals grow, they increase in mass. This increase in *measured mass* comes from the incorporation of atoms that were originally outside of the animals' bodies.

However, the analysis revealed that the Year 2 version's use of similar language was not consistent. For example, neither the animal growth science ideas nor the plant growth science ideas used the phrase *atom rearrangement*, and neither set of ideas was explicit about the production of new substances with *different properties* from the starting substances. This meant that students would not see that language in the animal or plant growth lessons and would not be asked to be explicit about those precise phrases when giving examples of science ideas.

Coherence. The Year 2 version of the unit was also analyzed for content coherence. Lessons had been shown to align with the science ideas, the first step in a coherence analysis. However, attempts to map the science ideas, which could show how well they were connected throughout the unit, revealed some notable omissions. The analysis revealed that in the Year 2 unit (a) initial science ideas about chemical reactions did not emphasize the production of new substances with different characteristic properties, (b) science ideas for animal growth and plant growth did not focus on the production of substances with different characteristic properties from the starting substances, and (c) science ideas about plant growth did not include a statement linking plant growth to an increase in measured mass. As a result, these science ideas were also missing in the unit's lessons and activities. For example, while students examined data on properties of substances and compared properties of ending substances with those of the starting substances, they were not asked to use their observations as examples of a science idea. Moreover, neither animal growth nor plant growth lessons included data on properties of substances. Rather, the lessons focused exclusively on atom rearrangement. Lastly, the lessons on plant growth did not ask students to reconcile plant growth with the conservation of matter, as had been done for animal growth. The example below shows the questions in the SE and the suggested responses in the TE that asked students to relate animal growth to atoms/mass coming in from the environment:

1. How can atoms and molecules help us explain animal growth?
   When animals eat food, they are taking in atoms from the environment. Chemical reactions occur to rearrange those atoms so that they become part of molecules in the materials that animals use for growth or repair. Because those atoms have mass, when they are added to animals, the atoms increase the mass of the animal body.

2. Think back to the rusting of iron reaction and the models you built to show how rusting increases the measured mass of iron.
   a. How is growth in animal bodies like rusting?
      Both take in atoms from the environment.
      Chemical reactions take place.
      New substances are formed.
      The atoms that are taken from the environment and rearranged become part of the system and cause an increase in mass.
   b. How is growth in animal bodies different from rusting?
      In rusting, the atoms that increase the mass come from the air. In growth, the atoms come from food. (Lesson 16, p. 129)

The order in which students encountered the science ideas was also examined to see if the sequence told a coherent story from the student's point of view. This analysis revealed both strengths and weaknesses. A strength identified in the sequence was that it started with science ideas most proximal to students' experiences, e.g., the chapters on animal and plant growth first introduced science ideas about the composition of animal and plant body parts that serve as food for animals before zooming in to ideas about the molecules making up body parts and the chemical reactions needed to make protein and carbohydrate polymers (Table 1b). In contrast, most middle and high school biology textbooks start with molecules and never relate the molecular level to the tissue (e.g., animal muscles and tendons) or organism level (e.g., a baby growing, a lizard re-growing a tail) that are easier to observe (AAAS, 2005). On the other hand, the analysis revealed that some science ideas, though important and interesting, seemed to digress from rather than build toward the learning goals about chemical reactions being required for animal and plant growth. For example, the science idea about representing atoms and

molecules with different types of models (Table 1a) could contribute to a storyline about the role of models in science but does not directly contribute to the storyline of animal and plant growth. Other science ideas described details of polymer formation that were not essential for understanding that the growth of animals and plants requires chemical reactions.

Instructional time needed. The Year 2 version of the unit was also analyzed to determine the approximate amount of instructional time that would be spent on each of the unit's learning goals. This analysis was carried out at the grain size of the learning goals rather than at the finer grain size of individual science ideas. Table 2 shows how the initial plan for teaching the unit estimated the instructional time, in minutes per lesson, that would be needed for each science content and practice learning goal and the total time needed for each learning goal across lessons. These time estimates were derived from information provided in the Year 2 TE.

For science content learning goals (e.g., New substances form during chemical reactions; atoms rearrange during chemical reactions.), the total number of minutes estimated for the lesson was assigned to that learning goal, because it was determined that all activities targeted it. As shown in the far right column of Table 2, the total time for the science content learning goals varied from 120 to 507 minutes (average 267 minutes). Times for learning goals on animal and plant growth (507 and 387 minutes, respectively) were higher than the average because those learning goals included more science ideas, whereas learning goals that included fewer science ideas were below the average.

For modeling learning goals, time was counted for (a) activities in which students learned about the models, (b) activities in which students were asked to model atom rearrangement or conservation, and (c) activities that included questions requiring students to interpret and/or draw conclusions from their models. As shown in the far right column of Table 2, time for modeling learning goals ranged from 30 minutes to 135 minutes (average 86 minutes). The larger amount of time for conservation was because the unit engaged students in modeling both mass conservation and changes in measured mass.

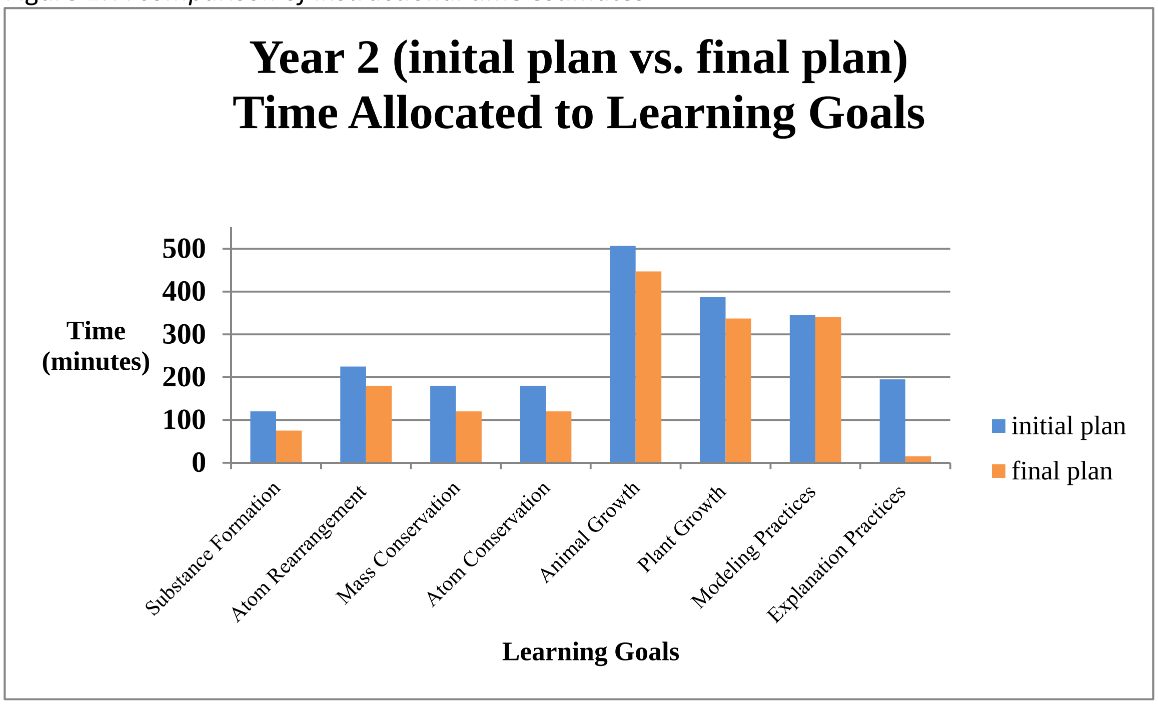
For explanation learning goals, time was counted for (a) activities within lessons in the SE that required students to write formal explanations and typically provided Claim/Evidence/Reasoning tables for them to complete and for (b) other activities in which the TE indicated that formal explanations were expected. As shown in the far right column of Table 2, time for explanation learning goals ranged from 35 to 70 minutes (average 49 minutes), with the higher times for the more complex reactions involved in animal and plant growth.

Table 2: ***Year 2 Initial Plan - Instructional Time Allocated***

Lesson #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	total
Time (Minutes)	45	75	45	45	45	45	45	45	45	75	60	45	45	75	110	45	60	45	110	60	45	60	45	30	75	1420
Learning Goals																										0
New substances form during chemical reactions		75					45																			120
Atoms rearrange during chemical reactions			45	45	45	45	45																			225
Modeling atom rearrangement			15	35	30	30																				110
Explaining new substance formation							35																			35
Mass is conserved in chemical reactions								45		75	60															180
Atoms are conserved in chemical reactions									45	75	60															180
Modeling conservation of atoms and mass									45	60	30															135
Explaining mass changes											45															45
Animal growth requires chemical reactions	22											45	45	75	110	45	60							30	75	507
Modeling chemical reactions in animal growth														15	15											30
Explaining animal growth															10		60							0	0	70
Plant growth requires chemical reactions	22																	45	110	60	45	60	45			387
Modeling chemical reactions in plant growth																			45	20			5			70
Explaining plant growth																						45				45

As the time for pilot testing the Year 2 version of the unit approached, practical constraints became apparent that required revising the initial plan for teaching the unit. The total time originally estimated for completing the 25 lessons had been 1420 minutes. For teachers with 42-minute class periods, the unit would require 34 class periods, plus two class periods for administering pre- and post-tests, or more than seven weeks in all. Even teachers with slightly longer class periods would not be able to complete the unit in the six weeks available. The only lessons that could be dropped without destroying the coherence of the content storyline were the four explanation lessons, and in the final plan, teachers were instructed to do so. As shown in Figure 1, eliminating the explanation lessons actually decreased the time spent on all of the learning goals except modeling, but the change clearly had the greatest impact on the explanation learning goals themselves.

Figure 1: *A comparison of instructional time estimates*



Feasibility. The Year 2 version of the unit was used by eight teachers in 28 classrooms, of which six were "gifted," five were "inclusion," and 17 were regular, grade level classes. All teachers who taught "gifted" classes also taught "inclusion" classes, which included both regular students and students with special needs. We collected information from teachers and students about whether teachers were able to complete the unit in the intended time. Teachers reported on their day-to-day pacing in each of their classes, and student notebooks provided detailed information on which activities or parts of activities were completed. We also observed and videotaped four lessons per teacher to determine how activities were carried out, e.g., whether students engaged in the activities themselves or observed demonstrations, whether students wrote answers to questions before or after a class discussion.

Table 3 presents findings on what teachers were able to accomplish with each class, based on an examination of their students' notebooks. Dark grey bars indicate which lessons were completed, and light grey bars indicate which lessons were significantly truncated. Discontinuities show which lessons

teachers skipped. The number of lessons completed by the eight teachers ranged from 8 to 17 (13.4 lessons on average), with the average completion rate for gifted classes (13.8 lessons) being a little higher than for the inclusion classes (12 lessons). Two of the four teachers who completed the most lessons had co-taught the unit in Year 1 with a member of the curriculum development team. One of these teachers kept accurate records of time devoted to each lesson in Year 2, which gave us a sense of what might be possible for other teachers using the unit a second time.

Students' notebooks also revealed that three teachers had typically not assigned the homework tasks, which meant that their students were not asked to read the science ideas or to list examples of them. As a result, the science ideas were never made explicit in those classrooms. This observation highlighted the need to make the role of the science ideas more integral to lesson activities.

Videotapes revealed that some classes bogged down during modeling activities. By comparing those classes with classes that did not have problems with modeling, we gained insights into the kinds of student and teacher supports that might help to increase efficiency across all classrooms. For example, we noticed that in some classrooms the students experienced considerable difficulty constructing three-dimensional models from two-dimensional drawings and that teachers spent considerable time troubleshooting students' incorrect models. As described in Kruse et al. (2013), the Year 3 version of the unit included modifications to modeling activities and added instructional supports for teachers to help them carry out the modeling activities more efficiently.

Table 3: *What teachers accomplished in Year 2*

Year 2 Lesson Completion by Teacher and Class Period																										Total Lessons Completed
	Lesson #																									
Teacher	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	
1																										17
																										17
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6																										8.5
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																										9.5
																										12
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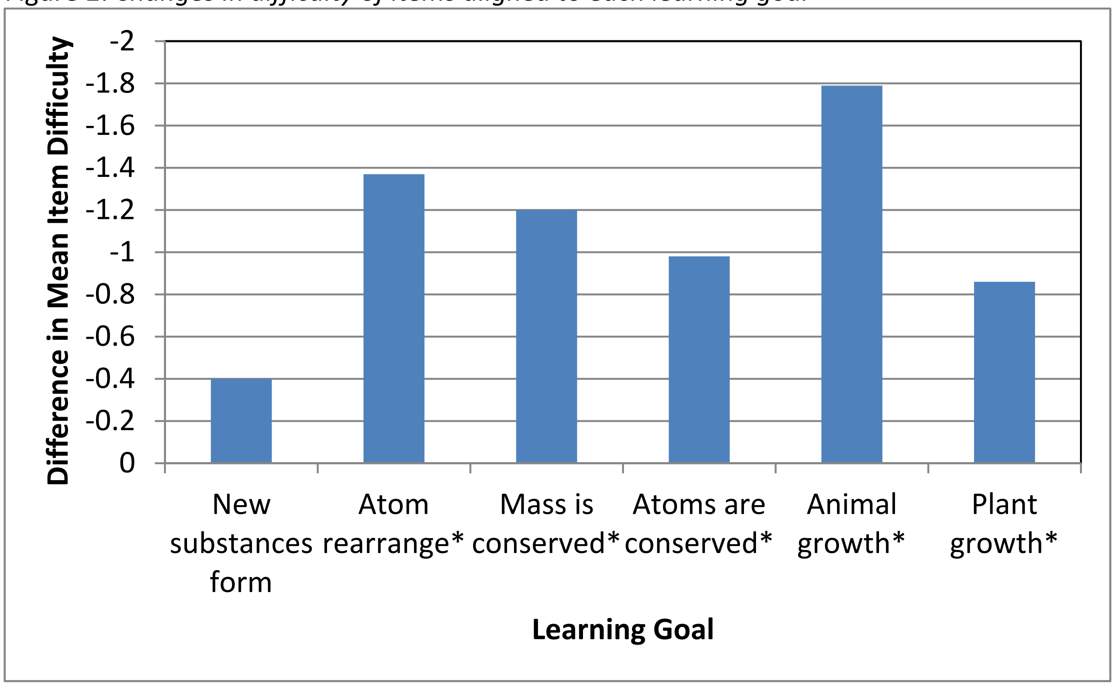
7																										12
																										12
																										12
																										12
																										9
8																										8
																										10

Student understanding. Before making changes to the curriculum unit and/or its targeted learning goals, we needed to try to distinguish between problems that were caused by students not having a chance to experience the lessons from problems caused by the lessons themselves. To do this, we examined the relationship between time spent on different learning goals and students' learning gains associated with those goals. As described in Herrmann-Abell, et al (2013), 89% of the students in Year 2 had increased ability measures from pre-test to post-test (that is, they were able to answer more test items correctly). Similarly, the estimated difficulty level of 49 out of 53 items decreased for students

from pre-test to post-test. Items showing little to no significant decrease in difficulty were those targeting ideas about the size of atoms (an idea not targeted in the Year 2 version of the THSB unit), the molecules of a substance determining its properties, and substances reacting to form new substances with different properties (the two latter ideas had received the least instructional time).

The graph shown in Figure 2 summarizes the findings for the content learning goals, comparing decreases in mean item difficulty from pre-test to post-test. An asterisk (*) indicates learning goals for which changes in mean item difficulty from pre-test to post-test were significant.

Figure 2: *Changes in difficulty of items aligned to each learning goal*



Variations in changes in mean item difficulty were consistent with variations in the amount of time that the final plan had estimated would be devoted to the learning goals: mean item difficulty decreased most on items targeting ideas about animal growth, for which the most amount of instructional time was estimated in the final plan, and decreased least on items related to ideas about how new substances form, for which the least amount of instructional time had been estimated.

To further explore the relationship between time spent on a learning goal and changes in item difficulty from pre- to post-test, we compared the performance of students who had not experienced plant growth lessons to students who experienced either of two plant growth lessons (no students experienced both). One of the plant lessons used results of radioactive labeling experiments to show that both the carbon and the oxygen atoms of glucose come from CO_2, and the other plant lesson demonstrated that the increase in mass of a potted willow tree is far more than the decrease in the mass of the soil. On two items that assessed the meaning of terms, no difference was noted in the performance of the two groups of students. However, on an item that assessed students' understanding of where a plant's mass comes from, students who had experienced one of the plant growth lessons outperformed students who had not. The item asks students about the relationship between soil minerals and plant growth: "What is true about plants and the minerals in the soil where they grow?" The correct response, "Plants take in minerals from the soil, but those minerals make up only a very small amount of the new mass of the growing plant" was selected by about 33% of both groups of

students on the pre-test. On the post-test, there was no change in the performance of students who had not experienced a plant growth lesson, whereas 70% of students who had experienced one of the plant growth lessons selected the correct response. Similarly, while about half of both groups of students had initially selected the distractor “Plants take in minerals from the soil and those minerals make up most of the new mass of the growing plant,” only the group who completed one of the plant growth lessons showed improvement, with only 21% selecting that incorrect answer choice. It should be noted that each group of students included an equal number of gifted and inclusion students, so the academic characteristics of the students does not account for the difference in performance between the two groups. This finding gave us reason to expect that students would be capable of understanding this and perhaps other science ideas about plant growth if they could experience the lessons.

Revisions to Learning Goals for the Year 3 Version of the Unit

Results of the analysis and feasibility study made it clear that for the Year 3 implementation of the unit, lessons would have to be cut, and this would have implications for the number of learning goals that could be effectively targeted. Because modeling and explaining phenomena were essential activities for promoting student understanding, we agreed to maintain the focus on these science practices and to reduce the number of science ideas. At the same time, persistent difficulties revealed by the student post-test data suggested that some essential science ideas and activities targeting them might be missing from the unit. Decisions were made to (a) eliminate non-essential parts of the content storyline, (b) combine some science ideas to make them more useful for explaining phenomena, and (c) add science ideas to fill gaps in the storyline.

Streamlining the Content Storyline

The AAAS-BSCS team agreed that ideas about the chemical reactions by which animals make carbohydrate polymers and about the chemical reactions by which plants make protein polymers were not essential to a fundamental understanding of the importance of chemical reactions to animal and plant growth, which was the ultimate goal of the THSB unit. Chemical reactions by which animals make carbohydrate polymers help explain how invertebrates make chitin needed for their exoskeletons. While interesting for explaining properties of biomaterials—the amount of chitin versus protein determines how hard (e.g., lobster shell) or soft (e.g., insect leg coverings) an exoskeleton is—the lesson on chitin production was thought to be less proximal to the animal growth content storyline and was dropped. Chemical reactions that remained—production of proteins for muscles, tendons, and scales—would have to suffice. A lesson on chemical reactions involved in plant production of proteins, which are needed to explain why herbivores (and vegans) can survive on a plant-based diet and why minerals from the soil contribute only a small amount of mass to growing plants, was also dropped in the interest of streamlining, leaving only lessons on photosynthesis and cellulose production to account for plant growth. Consequently, the Year 3 version of the unit omits the following science ideas and associated activities:

> Plants use a chemical reaction involving glucose molecules and nitrogen atoms to make amino acid monomers. Plants use these amino acids to build protein polymers that become part of their body structures.
>
> The nitrogen that plants use to make proteins comes from nitrogen-containing molecules that plants take in from the soil.

Also eliminated was a science idea about models that had been included to help students build an understanding of the nature of science:

> We can represent atoms and molecules with different types of models. Models can show some aspects of the real thing but not all aspects. Different models can show different things or provide different information about molecules.

While students would continue to use a variety of models to make sense of chemical reactions, they would not spend time reflecting on their use of the models.

Strengthening the link between Science Ideas and Explanations
As noted previously, the Year 2 version of the unit had listed science ideas in the SE and asked students to list examples of each in homework assignments at the end of the relevant lessons. Consequently, the science ideas were only made explicit to students who completed the homework assignments. As described in Kruse, et al. (2013), the Year 3 version has made science ideas more integral to explanations by asking students to list examples of science ideas before writing explanations and then to list the science ideas that would be needed for each explanation. To better serve the explanation writing activities, the science ideas have been modified. For example, we eliminated the isolated Year 2 science idea about mass conservation and added a statement to another Year 2 science idea that linked atom conservation to changes in measured mass as shown below, with the added part in *italic*:

> The measured mass of reactants and products is not always the same as the total mass. The measured mass changes if reactants or products (often gases) enter or leave an opened container. *This is because atoms that make up reactants or products enter or leave the container. When measured mass changes, it is because we have not measured the mass of all of the atoms involved in the chemical reaction.*

This new version of the science idea better serves students in explaining mass changes in open systems in non-living contexts (e.g., iron rusting) and in living organisms (e.g., plant growth).

Filling Gaps in the Content Storyline
In Year 2, students had persistent difficulties in linking substance transformation during chemical reactions to atom rearrangement, suggesting that ideas about substance transformation should be made more explicit in the unit. Hence, in the Year 3 version of the unit science ideas about substance transformation have been added and linked to science ideas about chemical reactions by emphasizing the production of different substances as shown below in *italic*:

> Changes during which starting substances interact to form new substances are called chemical reactions. The ending substances of a chemical reaction can be recognized as new substances because they have different properties from the starting substances.
>
> There are many different proteins, which have different characteristic properties, and are therefore different substances.
>
> Different carbohydrate molecules have different characteristic properties, and are therefore different substances.
>
> The process by which proteins from food become part of animals' body structures involves chemical reactions in which the proteins from food are broken down into amino acid monomers, and these monomers are used to build *different* protein polymers that make up body structures.

Moreover, while the animal growth learning goal in the Year 2 unit had included a science idea reconciling the mass increase that accompanies growth with conservation principles, the plant growth learning goal had not. Hence, for Year 3 we added the following idea:

> When plants grow or repair, they increase in mass. This increase in measured mass comes from the incorporation of atoms from molecules that were originally outside of the plants' bodies.

The net result of the revisions was to reduce the number of science ideas from 31 to 22 in the Year 3 version of the unit. The Year 3 science ideas are mapped in Figure 3; science ideas are shown in boxes, with new science ideas or phrases in **bold** typeface. A comparison of the set of science ideas for Year 2 and Year 3 is in Table 4.

The map in Figure 3 is similar to maps in *Atlas of Science Literacy* (AAAS, 2001; 2007) in the way that it lists ideas in text boxes, represents connections among ideas with arrows, and displays how more sophisticated ideas (at the top of map) might develop from less sophisticated ideas (at the bottom of map). However, the map in Figure 3 differs from *Atlas* maps in its purpose and, therefore, its curriculum specificity. Because the Figure 3 map was used to capture the "big picture" of the unit revisions and their implications for the revised content storyline of the unit, the map includes only the ideas and arrows that indicate connections that are relevant to the THSB unit. For example, science ideas 12-16 are targeted in Chapter 3 of the unit after students have encountered prerequisite science ideas 1, 3, 6, and 7 in Chapter 1. Furthermore, the prerequisite ideas shown in the map are somewhat curriculum specific; other curriculum materials might reverse the order of ideas in some cases.

Discussion

Since the beginning of the standards-based education reform movement some 30 years ago, finding curriculum materials to embody a standards-based vision of teaching and learning has proven to be extraordinarily challenging. Today's curriculum developers, ourselves included, face new challenges as we attempt to integrate the core science ideas with the cross-cutting concepts and scientific practices that are called for in the NRC *Framework*. At the same time, the real-world environment of the classroom continues to be unpredictable, which leads to additional challenges for the developer. Based on our experiences in Year 1 and Year 2 and our more recent work on revisions for the Year 3 version of the THSB unit, we can offer a few observations and conclusions that may be applicable to curriculum development efforts not just in science but in other disciplines as well.

Opportunity to learn is key. Our results from Year 2 strongly suggest that the time needed for students to achieve science learning goals that integrate the NRC *Framework's* core disciplinary ideas, cross-cutting concepts, and scientific practices is probably much greater than schools currently provide. Given the sobering data on what teachers could actually accomplish in the six weeks available to them, we had to make some critical choices about which ideas to keep and which to eliminate. In the end, our six-week unit managed to do a respectable job of targeting most of two core science ideas in conjunction with aspects of two science practices and several crosscutting concepts—explicitly Energy and Matter: Flows, Cycles, and Conservation and implicitly aspects of Patterns, Cause and Effect; Scale, Proportion, and Quantity; and Systems and System Models. This is actually quite efficient, given that other curriculum developers working in this same topic area have estimated that it would take 16 weeks for middle school students to gain the foundation in chemistry needed and to apply that knowledge to phenomena in living systems (Krajcik & Reiser, 2006). With an additional two weeks of instructional time and using a similar approach that also targets science practices and crosscutting concepts, the THSB unit could probably incorporate the ideas about energy as originally intended. If so, that would mean approximately eight weeks, or 40 one-hour class periods of instruction, to address learning goals that are described in only two out of

a total of 200 paragraphs across all of the core ideas in the NRC *Framework*. Assuming each goal would require about the same amount of time (20 hours per paragraph), then the total set would require 4000 hours. Assuming an hour of science instruction each day from kindergarten through 12th grade (an estimate that is overly generous given that many elementary school students have little to no science instruction), that adds up to only 2340 hours devoted to science, not nearly enough to address all of the core ideas, practices, and crosscutting concepts that make up the three dimensions of science education outlined in the *NRC Framework*.

Design tradeoffs happen. Once the decision was made to streamline the unit for Year 3, we were faced with a host of difficult decisions about how to maintain the unit's pedagogical approach and coherent storyline while trimming away activities and, in some cases, entire lessons. We had to decide how to emphasize some aspects of the learning goals and deemphasize others and how to spend our limited instructional time more efficiently. All of these decisions involved tradeoffs of one sort or another. For example, given the difficulty of the ideas being taught, the time students needed to learn those ideas well, and the need to improve the overall coherence and comprehensibility of the unit, we found it necessary to (a) focus on only one part of a core idea (i.e., we focused on matter but not energy in the story of chemical reactions) and (b) exclude other relevant, important, and grade-appropriate ideas (e.g., cellular composition of all living things, food webs, and the role of decomposers). Similarly, giving students more time to learn how to develop complete scientific explanations would mean having them spend less time on phenomena. For example, in the Year 3 version of the unit, students will not investigate the production of chitin (which insects, spiders, and crustaceans need to build their exoskeletons). Nor will students investigate the production of proteins by plants, an idea that would help explain why herbivores (and vegans) can survive on a plant-based diet. As a result, the revised unit expects students to generalize core ideas from fewer instances. Whether they will be able to do that is an open question. But even if they can, the elimination of these phenomena deprives them of a richer appreciation of chemical reactions in the world around them.

Similarly, given the time that was allocated to the unit and the need to maintain a coherent storyline, we also found it necessary to pass up opportunities for bringing ideas about the nature of science into the foreground for students. If more time had been available, for example, students could have connected their modeling experiences to instances where using models had helped scientists get ideas about how something in the real world could work (e.g., Watson and Crick's comment at the end of their seminal publication of the DNA structure, "It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material." (1953, p. 4356). Or students could have explored more deeply the role of evidence in scientific discovery. Although the unit frequently asked students to provide evidence for their claims using data that came from actual experiments carried out by scientists, the data had not been collected to test the specific claim that students were making. A discussion with students of how the real-world experiment had been designed and how the evidence supported the scientists' conclusions could have been used to build an understanding of the role of evidence in scientific investigation. Despite a strong commitment to the nature of science as a key aspect of science literacy, other learning goals were a higher priority at this stage of the unit's development. As we and other developers opt not to add time for reflection about the nature of science, it will be important to keep notes about missed opportunities that could be drawn upon in other units and in other grades.

Finally, in some cases we needed to trade off grade appropriateness for vivid and relevant real-world phenomena that could make a core idea concrete to students. For example, we decided to

introduce our middle school students to phenomena that involved high school level ideas about the production of protein polymers from monomers in order to make ideas about biological growth plausible to them. We will be monitoring the effects of all of these tradeoffs as we see how the revised unit plays out in the Year 3 feasibility test.

Monitoring all of the "moving parts" of the design process is essential. Given the iterative nature of the design process as well as the multiple sources of feedback to the design and the numerous "moving parts" involved, there is a real need to monitor and document the process, make sure that all of the intended procedures and analyses are carried out, and that the team attends to the effects of design decisions on the unit as a whole, not just on the specific activity or lesson that is being revised. This lesson is based not only on our own experiences as curriculum developers but also on the work of others with whom we have collaborated, particularly the research teams at the University of Michigan, Northwestern University, and San Diego State University who were responsible for the IQWST and the *Interactions in Physical Science* materials (Krajcik & Reiser, 2007; Goldberg, Bendall, Heller, & Poel, 2009). In both cases, we have benefited from the careful documentation of their efforts to apply many of Project 2061's curriculum analysis procedures to their own goals-driven curriculum design process (Krajcik, McNeill, & Reiser, 2008; Heller, 2001). In our own work, for example, we found that the detailed mapping of the revised Year 3 unit shown in Figure 3 was especially helpful. The mapping allowed us to check the flow of ideas from lesson to lesson to see whether the sequence made sense logically and instructionally and whether ideas and connections among them were actually present in the unit (Roseman, Stern, & Koppal, 2010). The time needed to do this mapping was not insignificant, and it may be necessary to task someone on the team with these monitoring and documenting responsibilities. As noted in Clements' 2007 description of a framework for curriculum research, "ideally one member is responsible…for taking a perspective of 'standing outside,' observing and documenting the curriculum development and research team's activities, decisions, and reasons for decisions (Lesh & Kelly, 2000)." We think the mapping process is worth the effort, not only as a formative tool for developers but as a tool for conveying the conceptual flow of the unit to users. As Kruse et al (2013b) has explained, we are exploring the use of the map in professional development for teachers who will be using the THSB unit.

Conclusions

In this paper we have detailed an iterative curriculum design process in which revisions were made to the learning goals of a six-week curriculum unit designed to help middle school students connect core chemistry and biology ideas to explain growth and repair in animals and plants. By describing the multiple sources of feedback that informed the revisions, the various tradeoffs that were considered, and the rationale for each design decision, we have tried to illustrate some of the challenges involved in developing curriculum materials that seek to address the three dimensions of science learning recommended in the NRC *Framework* and in earlier standards-based documents such as AAAS's *Science for All Americans* and *Benchmarks for Science Literacy*.

Next steps. The Year 3 version of the *Toward High School Biology* unit is now in its final round of feasibility testing, and a concurrent small-scale randomized control trial is underway to compare use of the unit to a "business as usual" treatment. We will be monitoring the unit's performance carefully through classroom observations, analysis of student work, and measurements of student and teacher knowledge. On the basis of those results, we expect to be ready to mount a full-scale study to examine the efficacy of the unit in 2014.

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Table 1a: *Physical Science Ideas Targeted in Year 2 Version of the* Toward High School Biology *Unit*

Substances react chemically in characteristic ways. In a chemical process, the atoms that make up the original substances are regrouped into different molecules, and these new substances have different properties from those of the reactants. The total number of each type of atom is conserved, and thus the mass does not change. Some chemical reactions release energy, others store energy. (NRC, p. 111)

New substances form during chemical reactions.

- Every substance has a unique set of properties, such as color, odor, density, melting point and boiling point. Scientists can measure these properties and use them to tell one substance from another.

Atoms rearrange during chemical reactions.

- For many substances, a molecule is the smallest part of that substance. A molecule is made up of two or more atoms connected together in a specific arrangement.
- Atoms and molecules are extremely tiny—so tiny that we cannot even see them under the highest-powered microscopes. Substances that we can see are made up of huge numbers of atoms and molecules.
- There are many different types of atoms that combine in different ways to make up the molecules of different substances.
- The properties of a substance are determined by the different type, number, and arrangement of atoms that make up the molecules of the substance.
- We can represent atoms and molecules with different types of models. Models can show some aspects of the real thing but not all aspects. Different models can show different things or provide different information about molecules
- During chemical reactions, atoms that make up molecules of the starting substances separate from one another and connect in different ways to form the molecules of the ending substances. The starting substances and ending substances are made up of the same types of atoms and the same number of each type.
- Not all atoms of the molecules of the starting materials rearrange during a chemical reaction. Sometimes when forming new substances, groups of atoms stay together and only a few atoms from each starting molecule rearrange.
- Small molecules made up of carbon chains (monomers) can link together during chemical reactions to form large molecules (polymers) and water molecules. Monomers usually have groups of atoms—either oxygen and hydrogen atoms or nitrogen and hydrogen atoms—at two places on the molecule that are important for linking the monomers.
- Atoms still rearrange when polymers form, even though only a few are actually rearranged. Even though only a few atoms rearrange, polymer formation is a type of chemical reaction. The polymer is a new substance and has different properties than the monomers from which it formed.

Mass/atoms are conserved in chemical reactions.

- The amount of matter is constant during chemical reactions. If all of the reactants and products are measured, the mass of the reactants is the same as the mass of the products.
- The mass of a particular atom does not change, so a certain number of that type of atom will always have the same mass.
- Atoms are neither created nor destroyed during chemical reactions, so the total number of each type of atom remains the same.
- Because the mass of a particular atom stays the same and because the total number of each type of atom stays the same, the total mass of the matter stays the same when atoms are rearranged during chemical reactions.
- If the measured mass changes during a chemical reaction, it is because one or more substances, usually gases, have entered or left.

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Table 1b: *Life Science Ideas Targeted in Year 2 Version of the* Toward High School Biology *Unit*

Plants, algae (including phytoplankton), and many microorganisms use the energy from light to **make sugars (food) from carbon dioxide from the atmosphere and water through the process of photosynthesis, which releases oxygen. These sugars can be used** immediately or stored **for growth** or later use. **Animals obtain food from eating plants or eating other animals. Within individual organisms, food moves through a series of chemical reactions in which it is broken down and rearranged to form new molecules, to support growth,** or to release energy. In most animals and plants, oxygen reacts with carbon-containing molecules (sugars) to provide energy and produce carbon dioxide; anaerobic bacteria achieve their energy needs in other chemical processes that do not require oxygen. (NRC, p. 148)

Animal growth requires chemical reactions.

- The body structures of animals are made mostly of proteins.
- Proteins are polymers made of amino acid monomers.
- The amino acid monomers, and therefore the proteins made from them, are composed mainly of carbon, hydrogen, oxygen, and nitrogen atoms.
- Growth, repair, and replacement of animal body structures all involve chemical reactions during which proteins from food are used to make other proteins that become part of their body structures.
- The process by which proteins from food become part of animal's body structures involves chemical reactions in which the proteins from food are broken down into amino acid monomers, and these monomers are used to build new protein polymers that make up body structures.
- Atoms from the molecules that animals eat do not get incorporated into body structures without first going through chemical reactions.
- When animals grow, they increase in mass. This increase in measured mass comes from the incorporation of atoms that were originally outside of the animals' bodies.

Plant growth requires chemical reactions.

- The polymers that make up plants' body structures are mostly carbohydrate polymers. A few plant parts, like seeds, contain large amounts of protein polymers.
- Carbohydrate polymers are made of glucose monomers.
- Plants make the glucose monomers they use to build carbohydrates using a chemical reaction between carbon dioxide and water molecules.
- The process of making glucose monomers involves linking together carbon atoms that come from carbon dioxide.
- Oxygen molecules are another product of the chemical reaction that plants use to make glucose.
- Growth, repair, and replacement of plant body structures involve chemical reactions during which glucose molecules are used to make carbohydrate polymers. These carbohydrate polymers become part of the plant's body structures.
- Plants use a chemical reaction involving glucose molecules and nitrogen atoms to make amino acid monomers. Plants use these amino acids to build protein polymers that become part of their body structures.
- The nitrogen that plants use to make proteins comes from nitrogen-containing molecules that plants take in from the soil.
- Plants use minerals to grow, but minerals add a very small amount of mass to plants as they grow. Most of the increase in the measured mass of plants does not come from soil, water, or minerals. Most of the mass of plants comes from carbon dioxide.

Figure 3: *Science Ideas Targeted in Year 3 THSB Unit*

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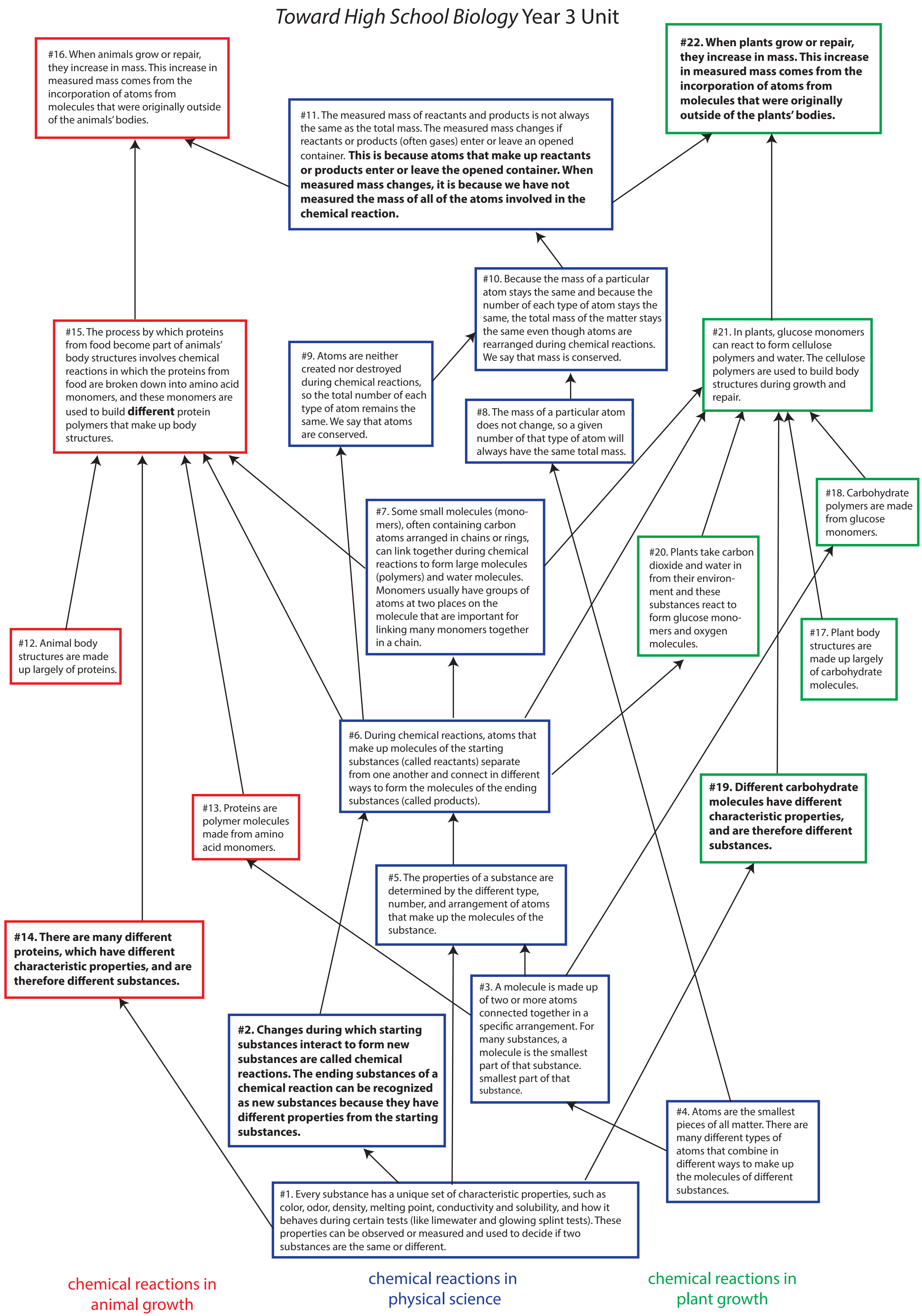

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Table 4: *Comparison of Year 2 and Year 3 Science Ideas*

Year 2 Science Ideas	Year 3 Science Ideas
New substances form during chemical reactions.	
Every substance has a unique set of properties, such as color, odor, density, melting point and boiling point. Scientists can measure these properties and use them to tell one substance from another.	Every substance has a unique set of characteristic properties, such as color, odor, density, melting point, conductivity and solubility, and how it behaves during certain tests (like limewater and glowing splint tests). These properties can be observed or measured and used to decide if two substances are the same or different.
	Changes during which starting substances interact to form new substances are called *chemical reactions.* The ending substances of a chemical reaction can be recognized as new substances because they have different properties from the starting substances.
Atoms rearrange during chemical reactions.	
For many substances, a molecule is the smallest part of that substance. A molecule is made up of two or more atoms connected together in a specific arrangement.	A *molecule* is made up of two or more atoms connected together in a specific arrangement. For many substances, a molecule is the smallest part of that substance.
Atoms and molecules are extremely tiny—so tiny that we cannot even see them under the highest-powered microscopes. Substances that we can see are made up of huge numbers of atoms and molecules.	*Atoms* are the smallest pieces of all matter. There are many different types of atoms that combine in different ways to make up the molecules of different substances.
There are many different types of atoms that combine in different ways to make up the molecules of different substances.	
The properties of a substance are determined by the different type, number, and arrangement of atoms that make up the molecules of the substance.	The properties of a substance are determined by the different type, number, and arrangement of atoms that make up the molecules of the substance.
We can represent atoms and molecules with different types of models. Models can show some aspects of the real thing but not all aspects. Different models can show different things or provide different information about molecules	
During chemical reactions, atoms that make up molecules of the starting substances separate from one another and connect in different ways to form the molecules of the ending substances. The starting substances and ending substances are made up of the same types of atoms and the same number of each type.	During chemical reactions, atoms that make up molecules of the starting substances (called *reactants*) separate from one another and connect in different ways to form the molecules of the ending substances (called *products*).
Not all atoms of the molecules of the starting materials rearrange during a chemical reaction. Sometimes when forming new substances, groups of atoms stay together and only a few atoms from each starting molecule rearrange.	
Small molecules made up of carbon chains (monomers) can link together during chemical reactions to form large molecules (polymers) and water molecules. Monomers usually have groups of atoms—either oxygen and hydrogen atoms or nitrogen and hydrogen atoms—at two places on the molecule that are important for linking the monomers.	Some small molecules (monomers), often containing carbon atoms arranged in chains or rings, can link together during chemical reactions to form large molecules (polymers) and water molecules. Monomers usually have groups of atoms at two places on the molecule that are important for linking many monomers together in a chain.

Table 4: *Comparison of Year 2 and Year 3 Science Ideas*

Atoms still rearrange when polymers form, even though only a few are actually rearranged. Even though only a few atoms rearrange, polymer formation is a type of chemical reaction. The polymer is a new substance and has different properties than the monomers from which it formed.	
Mass is conserved in chemical reactions.	
The amount of matter is constant during chemical reactions. If all of the reactants and products are measured, the mass of the reactants is the same as the mass of the products.	
The mass of a particular atom does not change, so a certain number of that type of atom will always have the same mass.	The mass of a particular atom does not change, so a given number of that type of atom will always have the same *total* mass.
Atoms are neither created nor destroyed during chemical reactions, so the total number of each type of atom remains the same.	Atoms are neither created nor destroyed during chemical reactions, so the total number of each type of atom remains the same. We say that atoms are *conserved*.
Because the mass of a particular atom stays the same and because the total number of each type of atom stays the same, the total mass of the matter stays the same when atoms are rearranged during chemical reactions.	Because the mass of a particular atom stays the same and because the number of each type of atom stays the same, the *total mass* of the matter stays the same even though atoms are rearranged during chemical reactions. We say that mass is conserved.
If the measured mass changes during a chemical reaction, it is because one or more substances, usually gases, have entered or left.	The *measured* mass of reactants and products is not always the same as the *total* mass. The measured mass changes if reactants or products (often gases) enter or leave an opened container. This is because atoms that make up reactants or products enter or leave the opened container. When measured mass changes, it is because we have not measured the mass of all of the atoms involved in the chemical reaction.
Animal growth requires chemical reactions	
The body structures of animals are made mostly of proteins.	Animal body structures are made up largely of proteins.
Proteins are polymers made of amino acid monomers.	Proteins are polymer molecules made from amino acid monomers.
The amino acid monomers, and therefore the proteins made from them, are composed mainly of carbon, hydrogen, oxygen, and nitrogen atoms.	
	There are many different proteins, which have different characteristic properties, and are therefore different substances.
Growth, repair, and replacement of animal body structures all involve chemical reactions during which proteins from food are used to make other proteins that become part of their body structures.	
The process by which proteins from food become part of animal's body structures involves chemical reactions in which the proteins from food are broken down into amino acid monomers, and these monomers are used to build new protein polymers that make up body structures.	The process by which proteins from food become part of animals' body structures involves chemical reactions in which the proteins from food are broken down into amino acid monomers, and these monomers are used to build different protein polymers that make up body structures.

Table 4: *Comparison of Year 2 and Year 3 Science Ideas*

Atoms from the molecules that animals eat do not get incorporated into body structures without first going through chemical reactions.	
When animals grow, they increase in mass. This increase in measured mass comes from the incorporation of atoms that were originally outside of the animals' bodies.	When animals grow or repair, they increase in mass. This increase in measured mass comes from the incorporation of atoms from molecules that were originally outside of the animals' bodies.
Plant growth requires chemical reactions	
The polymers that make up plants' body structures are mostly carbohydrate polymers. A few plant parts, like seeds, contain large amounts of protein polymers.	Plant body structures are made up largely of carbohydrate molecules.
Carbohydrate polymers are made of glucose monomers.	Carbohydrate polymers are made from glucose monomers.
	Different carbohydrate molecules have different characteristic properties, and are therefore different substances.
Plants make the glucose monomers they use to build carbohydrates using a chemical reaction between carbon dioxide and water molecules.	Plants take carbon dioxide and water in from their environment and these substances react to form glucose monomers and oxygen molecules.
The process of making glucose monomers involves linking together carbon atoms that come from carbon dioxide.	
Oxygen molecules are another product of the chemical reaction that plants use to make glucose.	
Growth, repair, and replacement of plant body structures involve chemical reactions during which glucose molecules are used to make carbohydrate polymers. These carbohydrate polymers become part of the plant's body structures.	In plants, glucose monomers can react to form cellulose polymers and water. The cellulose polymers are used to build body structures during growth and repair.
Plants use a chemical reaction involving glucose molecules and nitrogen atoms to make amino acid monomers. Plants use these amino acids to build protein polymers that become part of their body structures.	
The nitrogen that plants use to make proteins comes from nitrogen-containing molecules that plants take in from the soil.	
Plants use minerals to grow, but minerals add a very small amount of mass to plants as they grow. Most of the increase in the measured mass of plants does not come from soil, water, or minerals. Most of the mass of plants comes from carbon dioxide.	
	When plants grow or repair, they increase in mass. This increase in measured mass comes from the incorporation of atoms from molecules that were originally outside of the plants' bodies.